C.4 New Data /GPS

ANALYSIS OF TEMPERATURE AND HUMIDITY USING GPS RADIO OCCULTATION DATA IN PREPARATION FOR DATA ASSIMILATION

1 Introduction

The *Global Positioning System* (GPS) enables positioning with a very small receiver. The signals transmitted by the GPS satellites are sensitive to the atmosphere and can be used to perform soundings with the radio occultation technique (*e.g.,* Kursinski *et al.*, 1997). Radio-occultation data from the receivers measuring GPS signals provide all-weather temperature and humidity sounding capability at very high ($\sim$ 1-2 km) vertical resolution with some degree of self-calibration (*e.g.,* Kursinski *et al.*, 1995; 1996; 1997). The relatively high vertical resolution of the GPS measurement, its self-calibration, and its nearly all-weather capabilities make it a good candidate for use in data assimilation systems (DAS) and numerical weather prediction (NWP).

The DAO hosted researcher Paul Poli, of Météo France, to study assimilation methods for GPS data. The initial project was 5 months in duration and resulted in a full report (Poli, 1999). The project was completed in collaboration with Joanna Joiner of the DAO and Robert Kursinski of the Jet Propulsion Laboratory (JPL). Paul Poli has returned to the DAO for further research on GPS. GPS is one of the areas in which NASA, NCEP, and NESDIS plan to coordinate. Joiner is leading this task. A summary of the current results and future plans is given below.

2 The Retrieval Technique

In order to demonstrate its usefulness in a DAS or NWP system, a first step is to assess its impact on the analysis. A one-dimensional variational off-line analysis (1DVAR), meaning the data are not assimilated in the 3D DAS, constitutes a starting approach to which further enhancements can be made.

There are several possibilities for the actual observation quantity to be analyzed. For example, the refraction or bending angle may be analyzed. Alternatively, the GPS signal can be converted to refractivity N via the Abel Transform. There are advantages and disadvantages to each approach. For the former approach, complex raytracing models, accounting for 3-dimension gradient effects, could be used. However, these models have thus far been too expensive for operational use (T. Matsumura and J. Derber, *private communication*) . A less expensive bending angle model (Eyre, 1994) has been used to compare GPS data with NWP model fields (Healey, 1998). The use of refractivity requires a relatively simple forward model. However, this approach assumes the atmosphere to be spherically symmetric over the area in which the bending takes place. It is not clear how significant this assumption will be for data assimilation.

The chosen observable to be analyzed in this study is the refractivity. There are several ways to proceed with the analysis. One way to extract temperature (humidity) from the refractivity is to assume a humidity (temperature) profile. Alternatively, a 1DVAR approach resolves the ambiguity problem raised in the interpretation of these data. It enables retrieving temperature and humidity simultaneously at a reasonable computing cost. This is the approach used here.

The retrieval method is the minimum variance approach (*e.g.* Rodgers, 1976; Eyre *et al.*, 1993), solved by a quasi-Newton iteration, *i.e.*,

$$x_i = x^b + (H_i^T R^{-1} H_i + B^{-1})^{-1} H_i^T R^{-1} \left(y - h(x_i) + H_i(x_i - x^b) \right) \tag{1}$$

where i denotes the iteration number, x_i is the current state vector estimate, x^b is the background or first guess estimate, h is an observation operator relating the state variables to the observable and H is its linearized version, y is the observation vector, and B and R are the error covariances of the background and observations, respectively. The background and the observation errors are assumed to be unbiased and uncorrelated with respect to each other.

The state vector x, which contains the temperature and the humidity at various levels, is first set equal to the guess. After convergence of the iterative process, it represents a solution (the *analysis*). The analysis has an optimal position with respect to both the observations y and the background x^b. This notion of distance is defined in terms of a weighted sum involving the error covariance matrices of the guess B and the observations R. It represents a physical constraint that helps to select one solution among the infinite number of possible atmospheric profiles that would match the observations.

A one-dimensional (1D) forward operator h has been developed. It estimates the refractivity induced by the background information at the altitudes of the GPS observation. The refractivity, after ionospheric correction and neglecting liquid water (valid at L-band wavelengths), is related to atmospheric parameters by

$$N = b_1 \frac{P}{T} + b_2 \frac{P_w}{T^2}, \tag{2}$$

where b_1 and b_2 are constants, P is pressure, T is temperature, and P_w is water vapor partial pressure. The operator must then relate the refractivities on the analysis levels to the altitudes and location of the observation. The computation of the Jacobian matrix (H) is also needed in the retrieval. An exact calculation from the analytic derivative of the forward model was verified by comparison with a calculation from finite differences.

The principal sources of error in the GPS refractivity measurements are the result of an imperfect ionospheric correction, the spherical symmetry approximation in the Abel transform, and noise in the phase shift measurements (Kursinski *et al.*, 1997). The errors in refractivity are assumed to be 2% below 5 km altitude and 0.2% above. For the background, we used the error covariance matrix of Joiner and Rokke (2000).

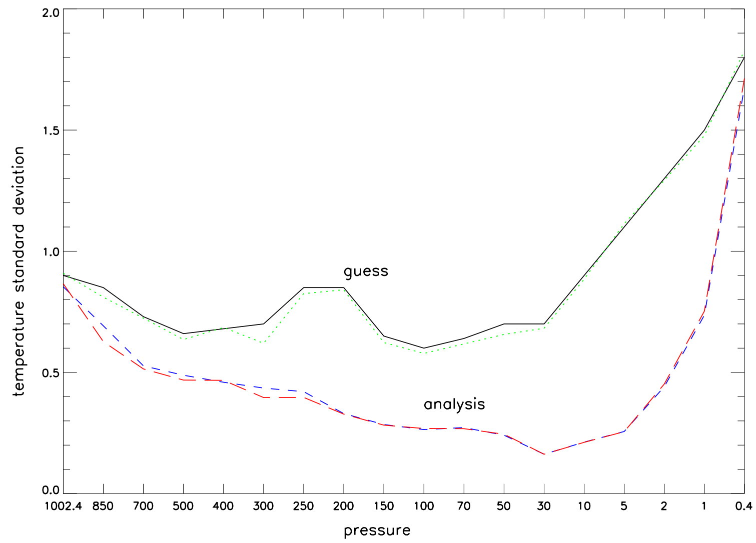

Figure 1: Theoretical standard deviation of analysis errors for temperature. Linear analysis - *solid line*: guess, *short dashes*: analysis; Monte-Carlo simulation - *dotted line*: guess, *long dashes*: analysis.

3 Theoretical Sensitivity Simulation

Temperature and humidity retrieval (analysis) errors can be estimated in advance, before having any real data, by using a linear error analysis (Rodgers, 1990). To validate this linear analysis, we also performed a fully non-linear Monte-Carlo simulation. In this simulation, we analyzed one thousand profiles for each of three typical atmospheric profiles at different latitudes. Errors were added to the background according to the assumed error covariance. Errors were similarly added to the observations. The results for temperature, shown in Figure 1, indicate that an analysis with GPS data should provide a significant improvement as compared with the background. This result holds for all three latitudes.

Figure 2 shows that the maximum impact for the humidity is to be expected in the lower troposphere in the Tropics. This is where the water vapor content is large enough to have a significant influence on the GPS refractivities. The Monte-Carlo approach verifies that the 1DVAR system works properly and that the linear error analysis is accurate. Similar results have been obtained by Healy and Eyre (2000).

4 Retrieval Sensitivities

GPS radio occultation data were collected in 1995 as part of the GPS/MET experiment. Approximately 800 occultations were collected during a time period known as 'Prime Time 3' (June-July 1995, when the encryption was turned off). They are analyzed in the framework of the 1DVAR technique described above using a 6 hour GEOS-Strat forecast as the background. The GEOS-collocated profiles are obtained by interpolating bi-linearly between four grid points. This grid spacing is 2° latitude

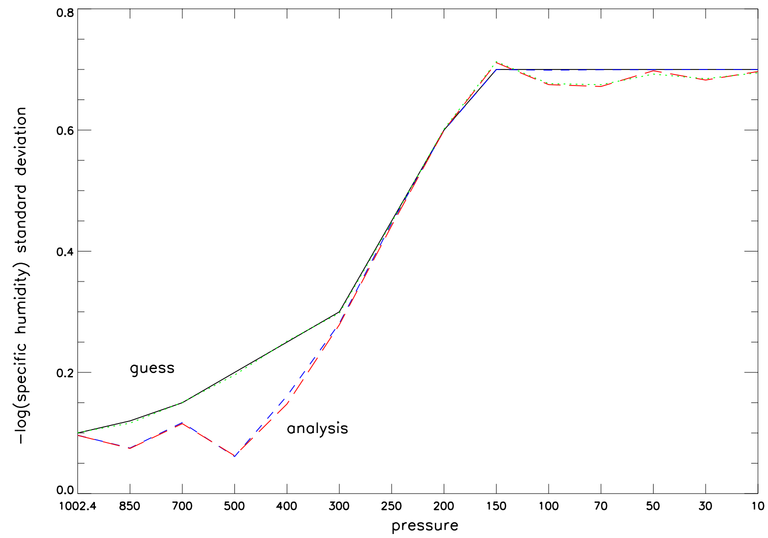

Figure 2: Similar to figure 1 except for $-\log$ specific humidity for a tropical profile.

$\times$ 2.5° longitude. Each observation is assumed to have taken place at the center of the 6-hour analysis window. In order to evaluate the impact of the GPS data, profiles of nearby radiosondes are also available.

The first analyses were performed on the 18 GEOS analysis levels. These analyses revealed the necessity of analyzing on more vertical levels, so that the small-scale structures seen by the GPS can be fully resolved. All subsequent analyses were performed on the 46 sigma levels of the GEOS model.

One unexpected result was the sensitivity of the analysis to the gravitational constant used in the analysis. Using different approximations for g can lead to differences of the order of 1K. This feature, specific to the GPS measurements, is related to the forward operator which maps atmospheric parameters from a set of pressures onto a set of altitudes.

The analyses were also found to be sensitive to the surface level pressure. By adding surface pressure to the state vector, any discrepancies in the definition of surface pressure (from the observation pre-processing and the background) are removed. The comparisons with radiosondes were improved with this new degree of freedom. The 1DVAR is able to move the whole refractivity profile downwards or upwards in terms of pressure in order to bring it closer to the observation, without having to modify the temperature at all the levels. This problem is intrinsic to GPS measurements. It is due to the fact that the background, expressed in terms of pressure levels, is confronted with observations in terms of altimetric levels and hence requires a reference to make the conversion.

5 Comparisons with Radiosondes

A validation study was performed using collocated radiosondes (RS). We compared the differences between the analyses and nearby radiosondes on the one hand, and

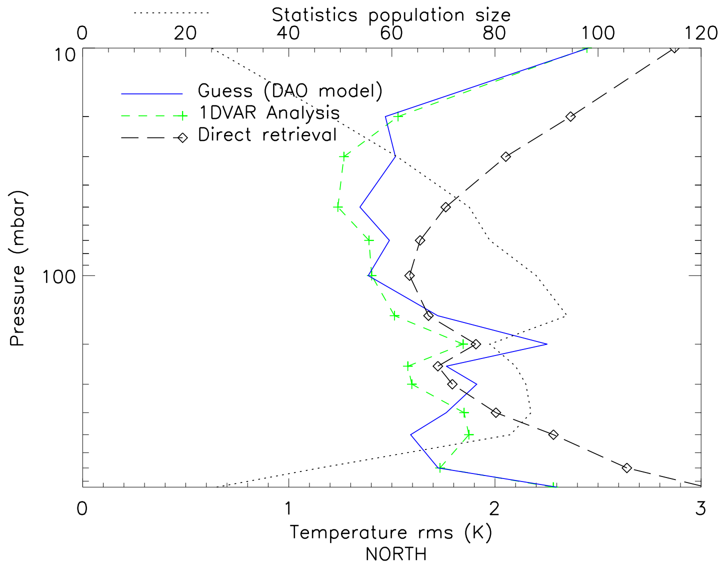

Figure 3: Statistics on temperature comparisons with radiosondes (+/- 3 hours, less than 280 km), n. hemisphere.

between the corresponding guess and the same radiosondes on the other hand. The RS collocation criteria are adjusted in order to find a good compromise between representativeness and the number of available profiles. With typical criteria (+/- 3 hours, chordal distance less than 280 km), about 150 collocations are found.

Both bias and standard deviation of the retrieval minus radiosonde are reduced as compared with the background above 200 hPa in the Northern hemisphere (above latitude 30°N) and in the Tropics (between 30°S and 30°N). Figures 3-4 show the root-mean square (RMS) statistics for the guess, the analysis, and also a direct retrieval which assumed a humidity profile and was not constrained to a model background. Figure 5 shows an example of the capacity of the GPS to resolve the tropopause in the analysis. Both retrievals are able to see the colder tropopause measured by the radiosonde. As expected for humidity, the analyses are very close to the guess except in the tropics. Figure 6 shows statistics for radiosonde collocations of humidity in the Tropics. The 1DVAR shows a slight improvement over the background in the lower troposphere, especially near 500 hPa as predicted in the simulation. However, it should be noted that the sample size was small.

6 Conclusion and future work

We have shown that GPS measurements significantly improve analyses of temperature in the troposphere and in the lower stratosphere as compared with the model background. The 1DVAR appears to provide some humidity improvement resulting from the GPS data in the tropical lower troposphere. The results obtained are reasonably consistent with those predicted by the theoretical study. The use of refractivity appears to enable the extraction of a significant amount of information at a relatively low computational cost. The 1DVAR appears to provide an improvement over the

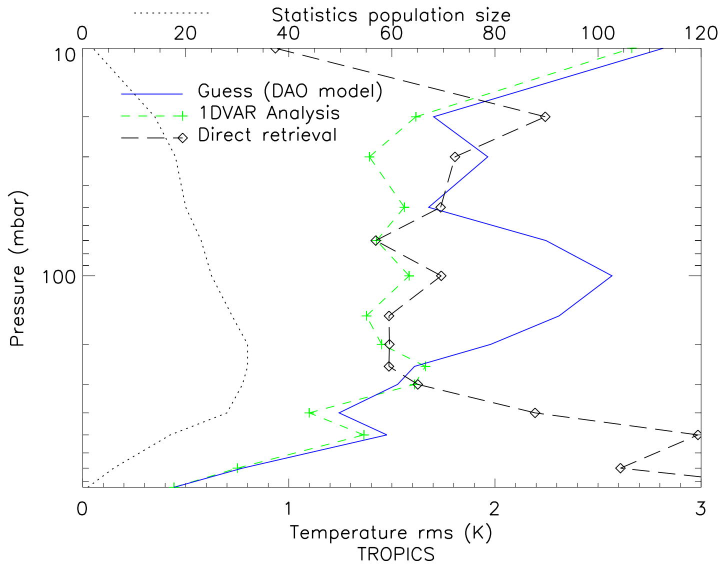

Figure 4: Similar to figure 3 but for the tropics.

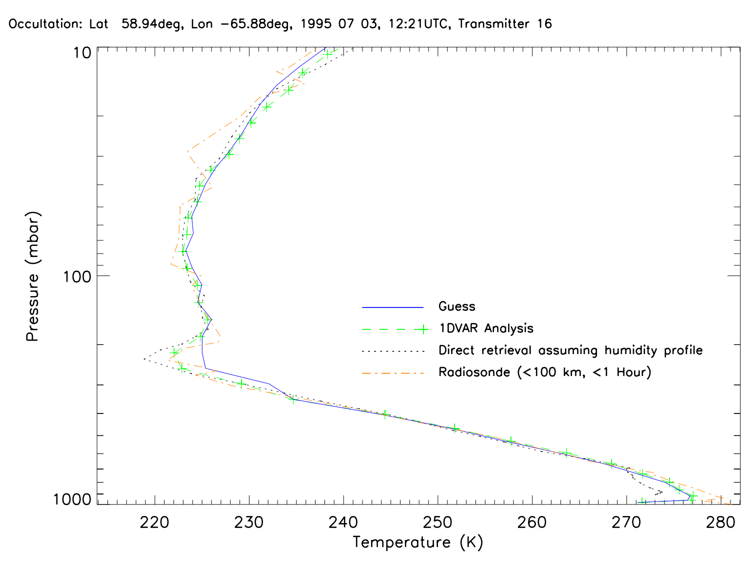

Figure 5: GPS temperature profile retrieval.

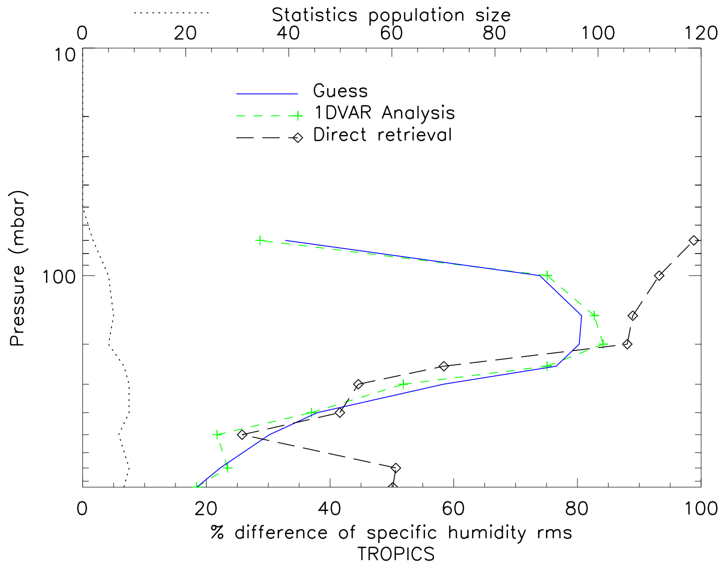

Figure 6: Similar to figure 4 but for percent of the specific humidity.

direct retrieval approach. The latter does not have the benefit of the information from an NWP model.

We plan to do similar validation studies during periods when the encryption is turned on. More work is also needed to effectively screen out erroneous data. These cases may include partial soundings where large refractivity gradients occur and the assumptions made in the forward model are violated. Finally, we will explore the possibility of an interactive 1DVAR including the Abel transform. In this type of approach, the upper boundary condition of the Abel transform can be specified from the DAS, potentially giving more accurate refractivities in the middle and upper stratosphere (> 35 km).

It remains to be seen how the errors resulting from the spherical symmetric approximation in the Abel transform affect the use of the data in a data assimilation context. A simulation of observations using fields from a model or data assimilation system with a full ray-tracing forward model would shed some light on this issue. This type of study could be conducted in the context of the Observing System Simulation Experiment (OSSE) setup that has been developed at NCEP. NCEP has also conducted preliminary assimilation experiments with a ray-tracing forward operator. An error analysis could be performed showing under what conditions the Abel transform produces significant errors.

We plan to conduct similar validation studies in the upper stratosphere for the temperature with other observing systems such as data from the Microwave Limb Sounder. With the limited amount of data available at this time, a full assimilation experiment would not provide statistically significant results. However, we are exploring the use of GPS data in model error estimation and instrument intercalibration.

Two additional GPS receivers have been recently launched on small satellites (Sunsat and Ørsted). More launches (COSMIC, Champ, and Sac-C) are planned in the next few years. As these data become available, we will assess their quality and will explore the use of GPS data operationally.

7 References

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